Algorithm for High-Resolution Soil Moisture Retrieval With Coincident Active and Passive L-Band Measurements

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Key Requirements for Soil Moisture/Freeze-Thaw

Spatial Resolution

- 10 km for soil moisture (Hydrometeorology)
- 1-3 km for freeze/thaw (Land carbon source/sink)

Coverage/Revisit

- 3 days for soil moisture
- 2 days for freeze thaw (at latitudes where applicable)

Incidence Angle

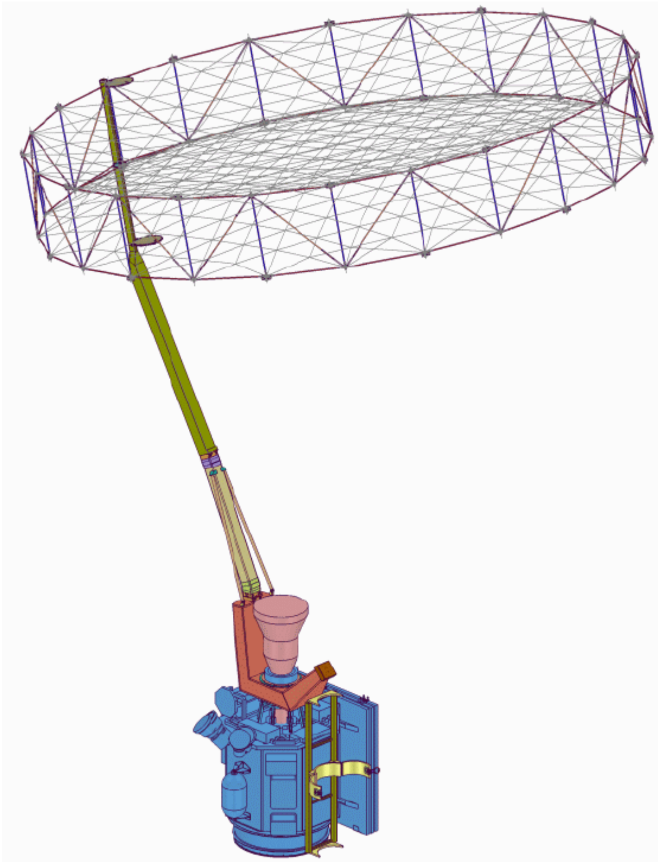
- Constant incidence angle between 35° - 50°.

Radar

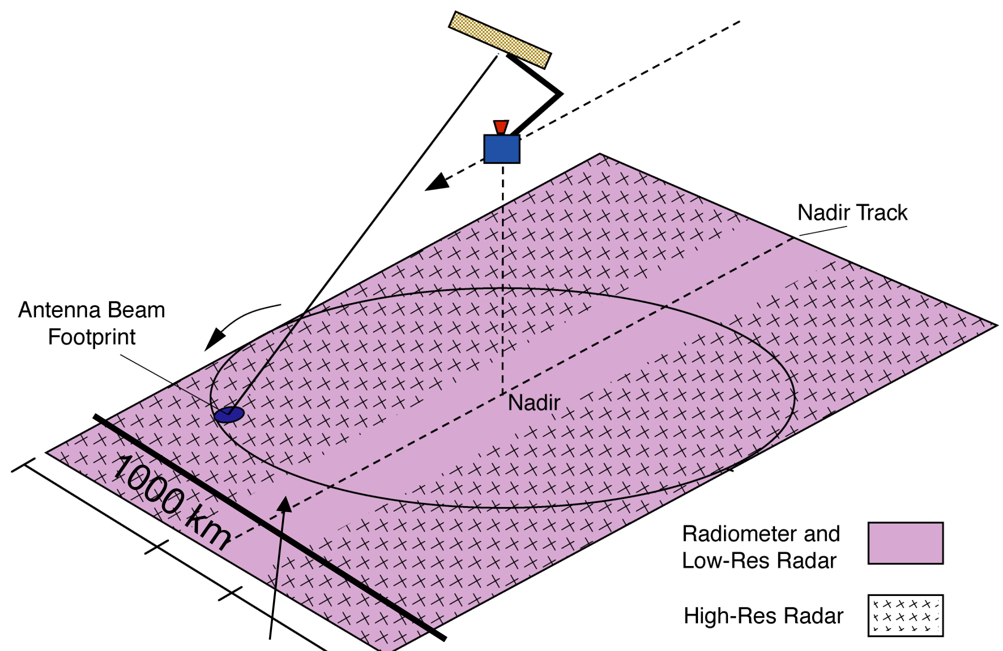
- Frequency: L-Band (1.26 GHz)
- Polarizations: VV, HH, HV
- Resolution: 3 km
- Precision (K_p noise): 0.85 dB
- Rel. Calibration Accuracy: 0.45 dB

Radiometer

- Frequency: L-Band (1.4 GHz)
- Polarizations: V, H, U
- Resolution: 40 km
- Relative Accuracy: 1.5 K



- Orbit: 670 km, sun-synchronous, 6 am/6 pm.
- Radiometer and radar share rotating 6 meter diameter reflector antenna.
- Reflector 14.6 rpm rotation rate, *fixed* 40 deg incidence angle.



Soil Moisture Active/Passive (SMAP) Mission

NASA HQ Workshop July 9-10, 2007
Arlington, VA

Objective:

Combine scene

3 km radar backscatter
(high resolution but noisy and no precise forward model)

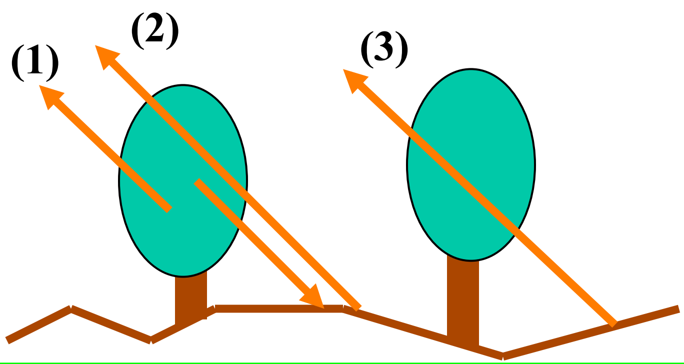
and

40 km radiometer brightness temperature
(low resolution but relatively accurate)

into *10 km hydrometeorology soil moisture data product*.

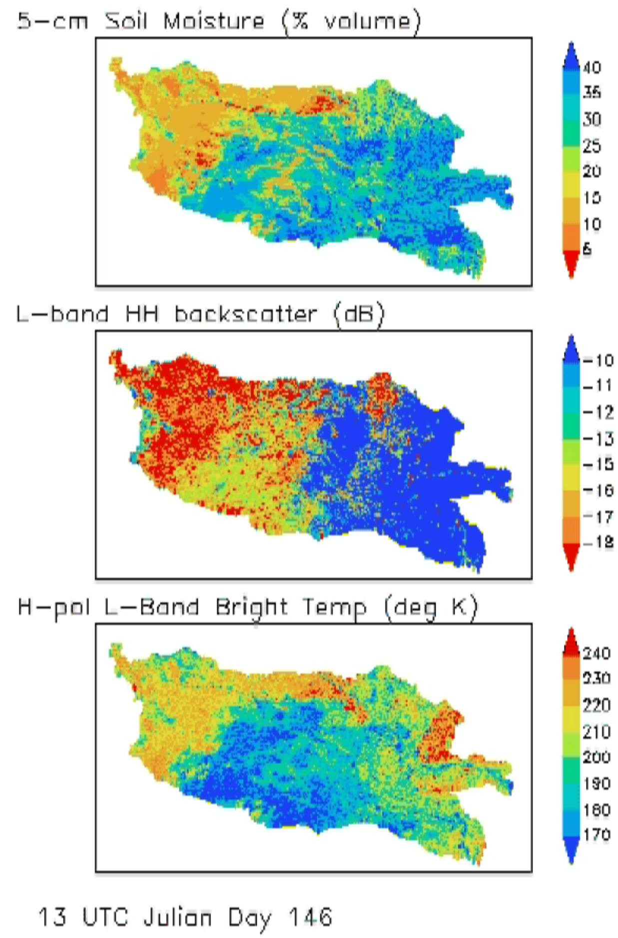
Identify algorithm assumptions in testable and separable units.

Evaluations with *Observing System Simulation Model* (OSSE)



$$T_{Bp}^{t} = T^{v} \cdot E_{p}^{v}(1 + R_{p}^{e} \cdot L_{p}) + T^{s} \cdot E_{p}^{s} \cdot L_{p} \qquad \textit{emission}$$

$$\sigma_{pq}^{t} = \sigma_{pq}^{v} + \sigma_{pq}^{sv} + \sigma_{pq}^{s} \cdot L_{pq}^{2} \qquad \textit{backscatter}$$



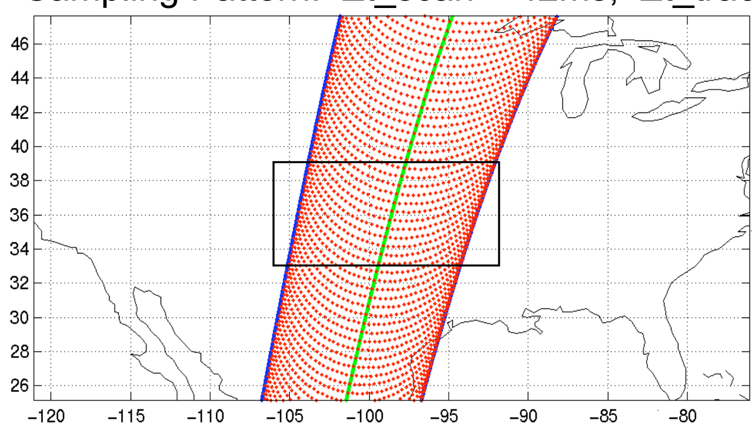
- Subscript p or pq : polarization
- L_{pq} or L_p : one-way attenuation factor
- Superscripts *t, v*, *sv*, and *s* are for total, vegetation, interaction and surface terms, respectively
- *T* : temperature

OSSE Design

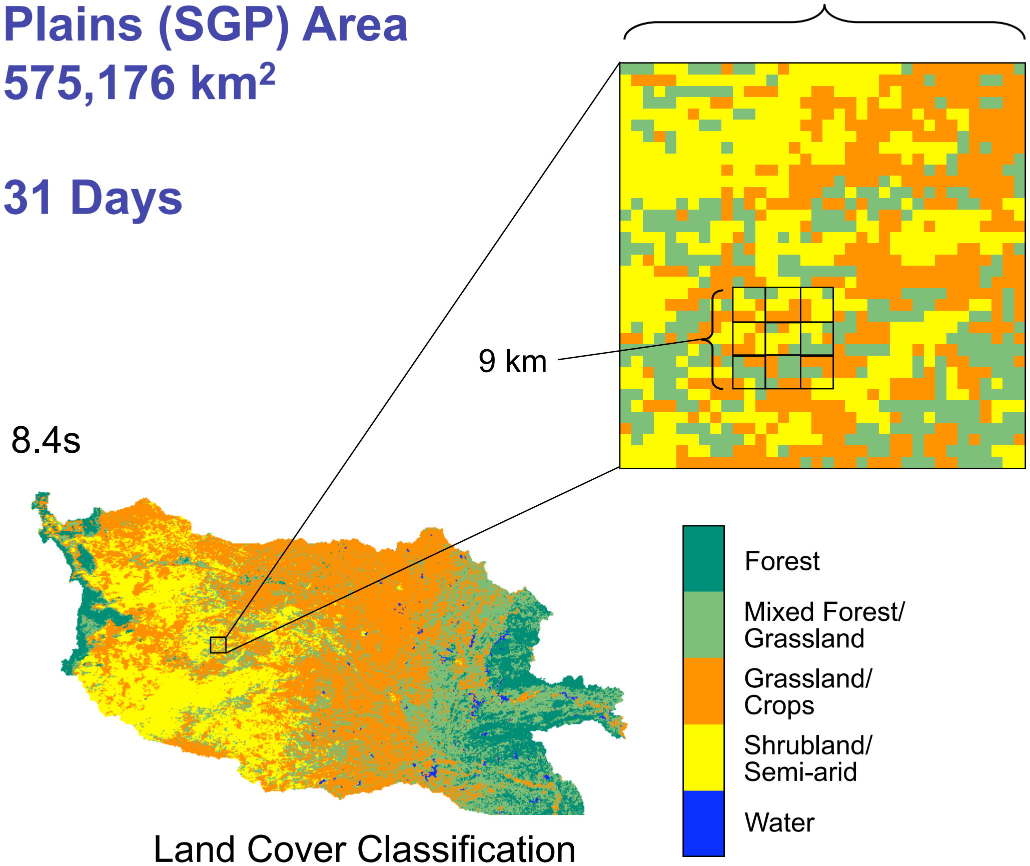
1 km resolution
Southern Great Plains (SGP) Area
575,176 km^2

31 Days

Sampling Pattern: Δt_scan = 42ms; Δt_track = 8.4s



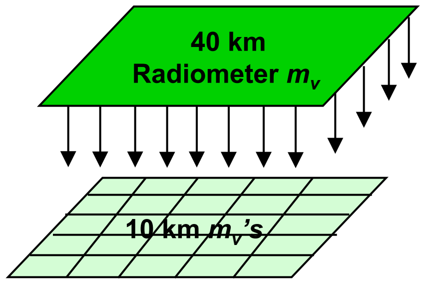
Land Cover Heterogeneity
(**1-km pixels**)



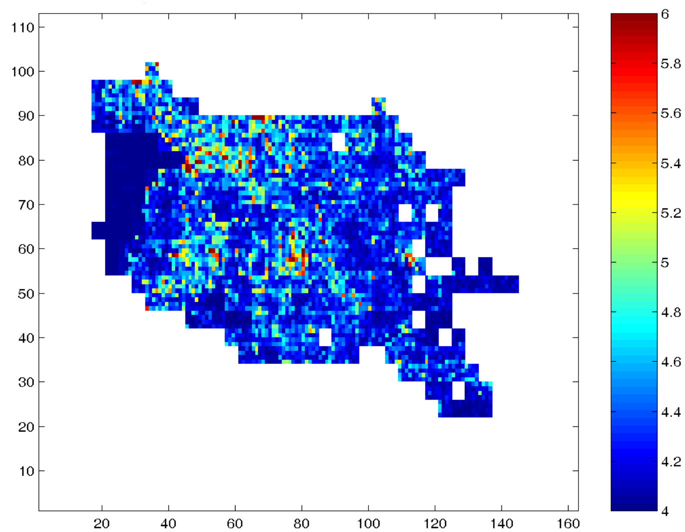
Land Cover Classification
(Grouped Categories)

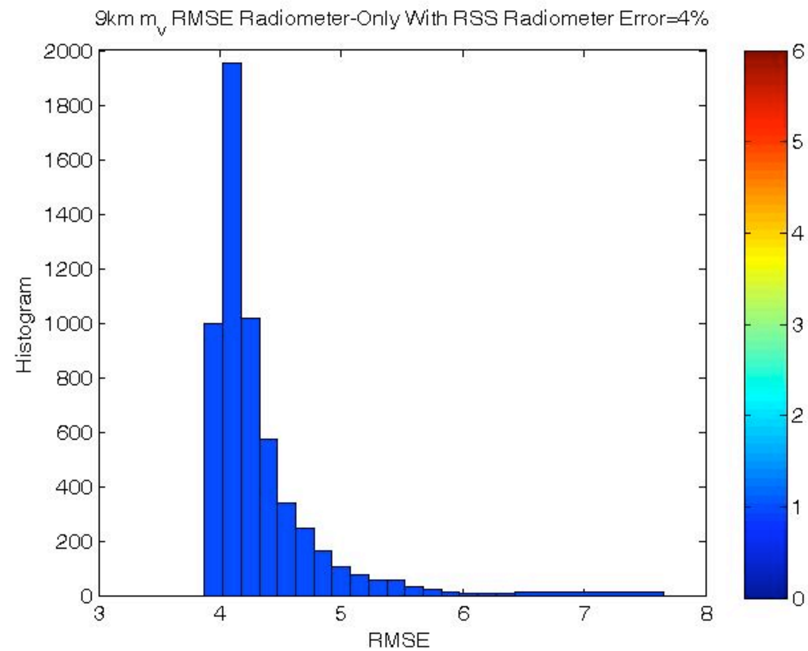
Minimum Performance Requirement

Assignment!



RMSE with RSS of Radiometer 4% Error



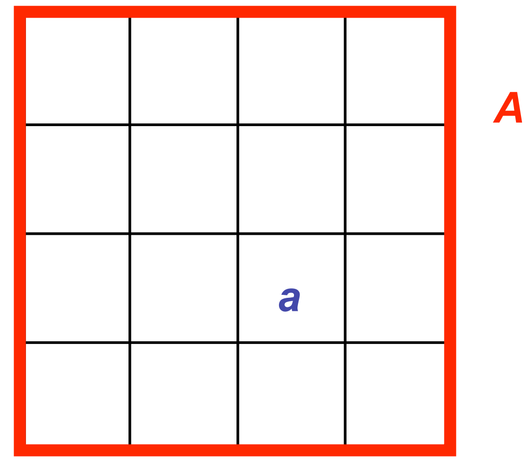


10 km soil moisture assignment error RSS with radiometer 4% RMSE

Definitions:

Scales ***A*** and ***a*** refer to radiometer and radar (aggregated to 10 km) respectively.

In the OSSE a=9 km and A=36 km.



Define the two linear operators:

Change: $$\Delta(\cdot)_t = (\cdot)_t - (\cdot)_{t-t_R}$$

where t_R is the revisit interval

Space-Average: $$\langle \cdot \rangle = \frac{1}{A}\int_A \cdot \, da$$

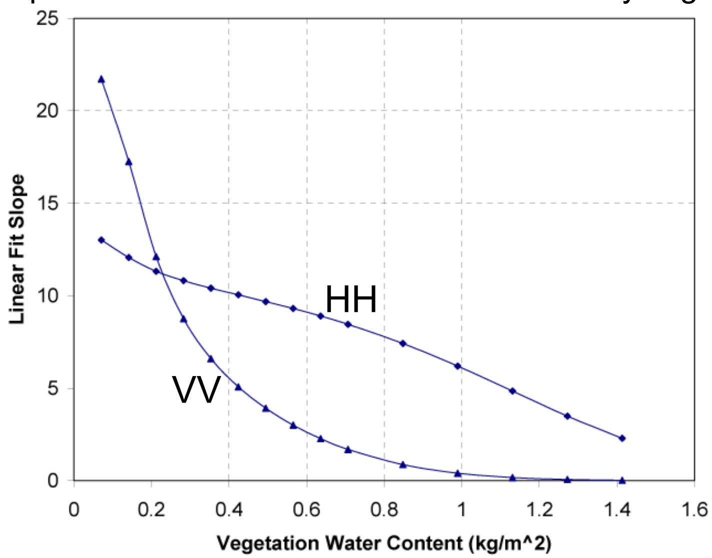
where A is the radiometer pixel area containing all a's.

Assumption #1: $$\theta(a,t) = \alpha(a) + \beta(a) \cdot \log[\sigma(a,t)]$$

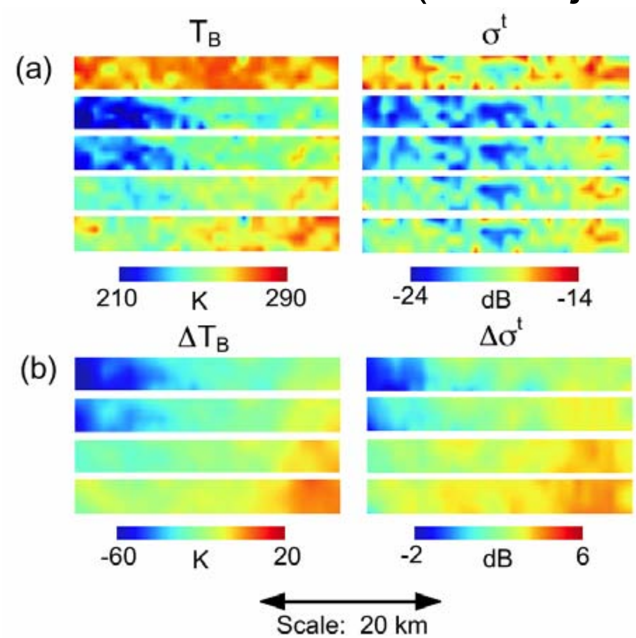
i.e., soil moisture at radar scale is linearly related to log of radar backscatter.

Theoretical Model (from van Zyl, Kim, Shi)

HH-pol dominant return is double-reflection
VV-pol dominant return from soil attenuated by vegetation



SMEX02 PALS Airborne Observations (from Njoku)



Time-Differences

Apply time-difference operator $\Delta\theta(a,t) = \beta(a)\cdot\Delta\log[\sigma(a,t)]$

and with spatial aggregation $\langle\Delta\theta(a,t)\rangle = \langle\beta(a)\cdot\Delta\log[\sigma(a,t)]\rangle$

Use definition of covariance $\operatorname{cov}\{x,y\} = \langle xy\rangle - \langle x\rangle\cdot\langle y\rangle$

to write

$$\langle\Delta\theta(a,t)\rangle = \operatorname{cov}\{\beta(a),\Delta\log[\sigma(a,t)]\} + \langle\beta(a)\rangle\langle\Delta\log[\sigma(a,t)]\rangle$$

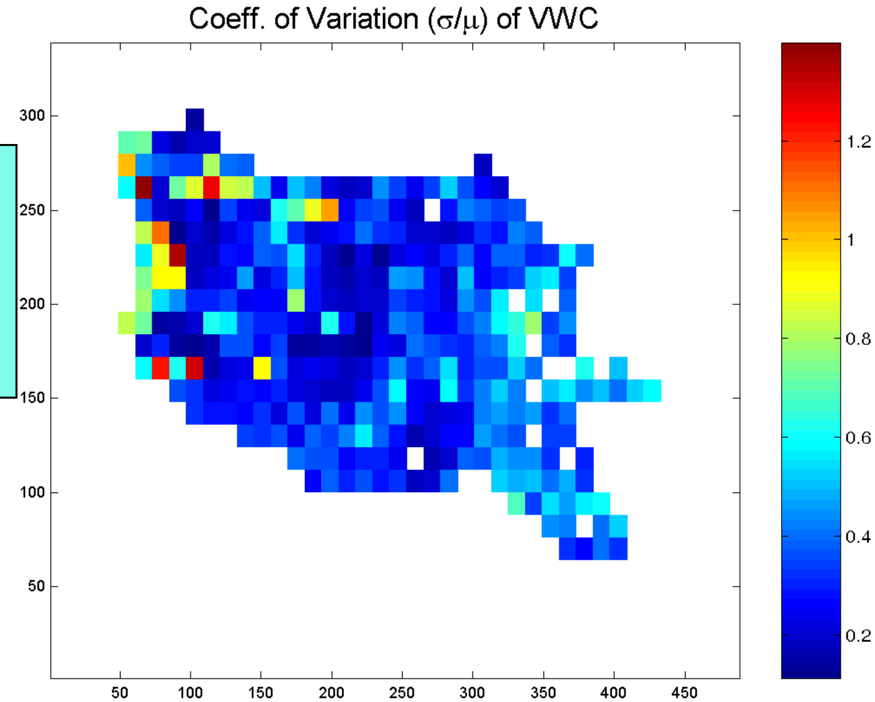
Assumption #2: $\operatorname{cov}\{\beta(a),\log[\sigma(a,t)]\} = 0$

i.e., slope β (due primarily to vegetation and roughness) and backscatter fluctuations (due to soil moisture) themselves are uncorrelated.

$$\langle \Delta\theta(a,t) \rangle = \langle \beta(a) \rangle \cdot \langle \Delta \log[\sigma(a,t)] \rangle$$
$$= \Delta\theta_{T_B}(A,t)$$

Assumption #3: $\beta(a) = \langle \beta(a) \rangle$

i.e., variations in vegetation type occur principally at scales larger than *A*.



Slope β can be estimated using regression of radiometer and radar data at scale *A*:

$$\Delta\theta_{T_B}(A,t) = \langle \beta(a) \rangle \cdot \langle \Delta \log[\sigma(a,t)] \rangle$$

Now we can use the definition of the time-change operator to write $\Delta\theta_{T_B}(A,t) = \langle\beta(a)\rangle \cdot \langle\Delta\log[\sigma(a,t)]\rangle$

as

Algorithm: $\theta(a,t) = \theta(a,t-t_R) + \langle\beta(a)\rangle\Delta\log[\sigma(a,t)]$

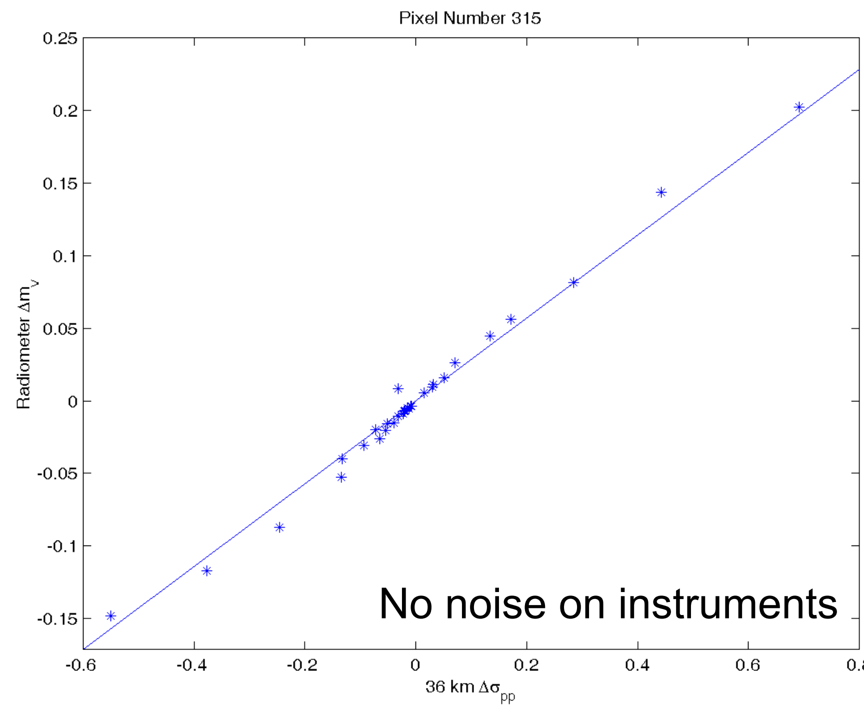
Slope $\langle\beta(a)\rangle$ is determined using radiometer and radar as they become available.

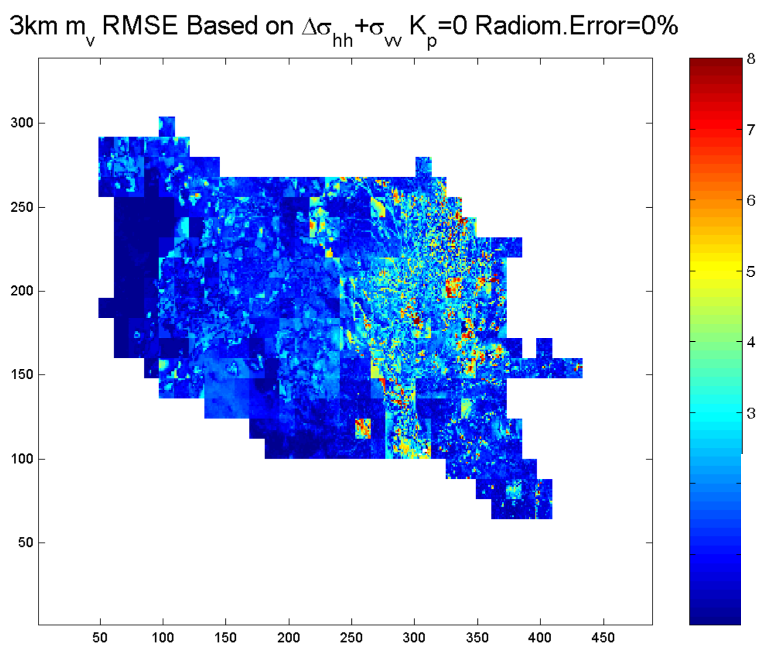
Regression of values starting at time t_0 until current time t :

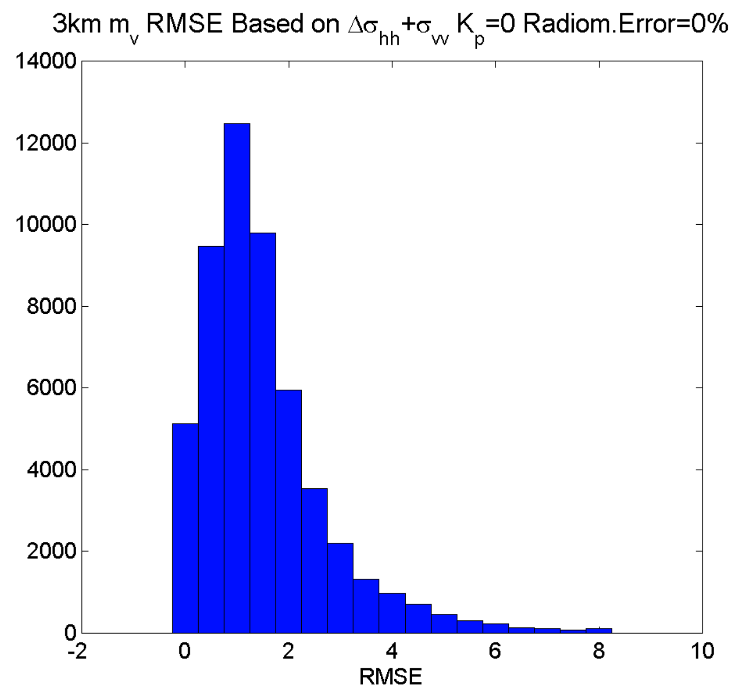
$$x_{[t_0,t]} = \left[\langle\log[\sigma(a,t_0)]\rangle \quad \cdots \quad \langle\log[\sigma(a,t)]\rangle\right]^T$$

$$y_{[t_0,t]} = \left[\Delta\theta_{T_B}(A,t_0) \qquad \Delta\theta_{T_B}(A,t)\right]^T$$

$$\langle\beta(a)\rangle = \frac{\left(x_{[t_0,t]} - \bar{x}\right)^T \left(y_{[t_0,t]} - \bar{y}\right)}{\left(x_{[t_0,t]} - \bar{x}\right)^T \left(x_{[t_0,t]} - \bar{x}\right)}$$



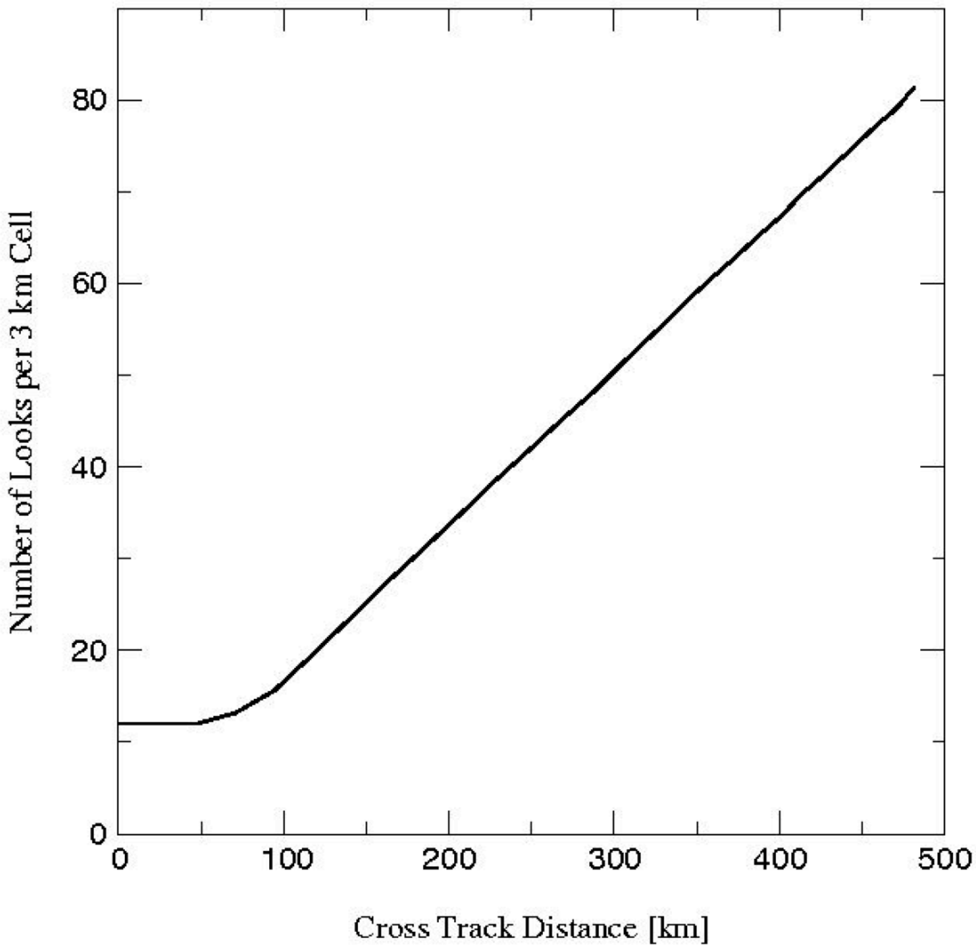


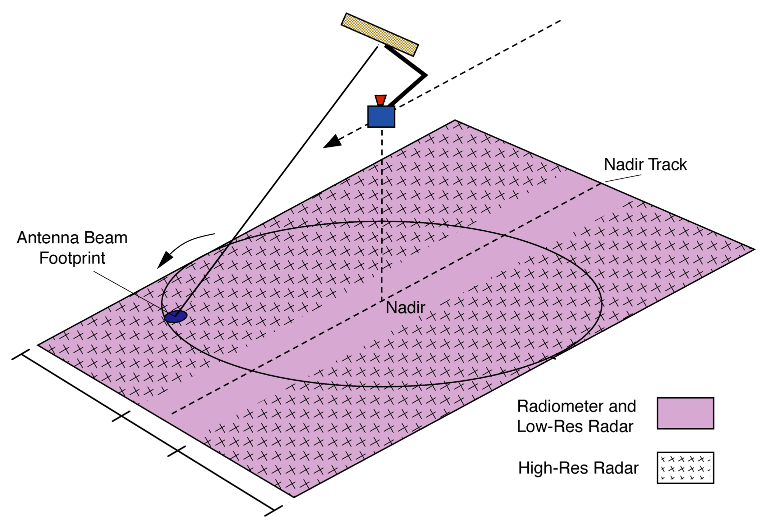


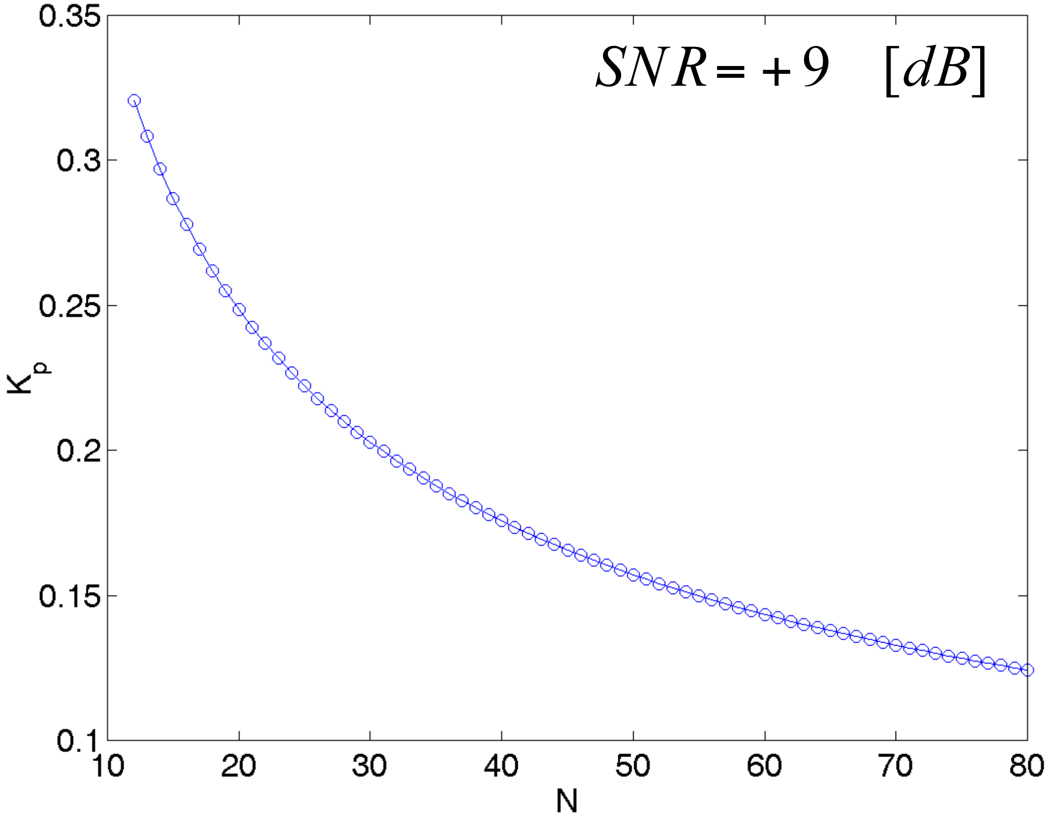
No instrument noise

“Cost” of algorithm assumptions

Radar Noise Level



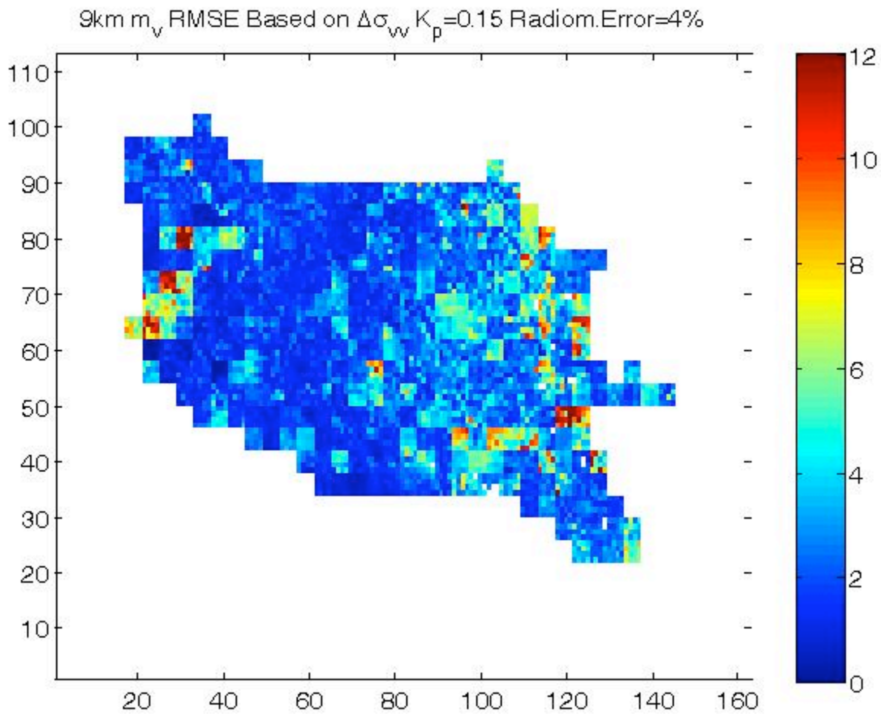




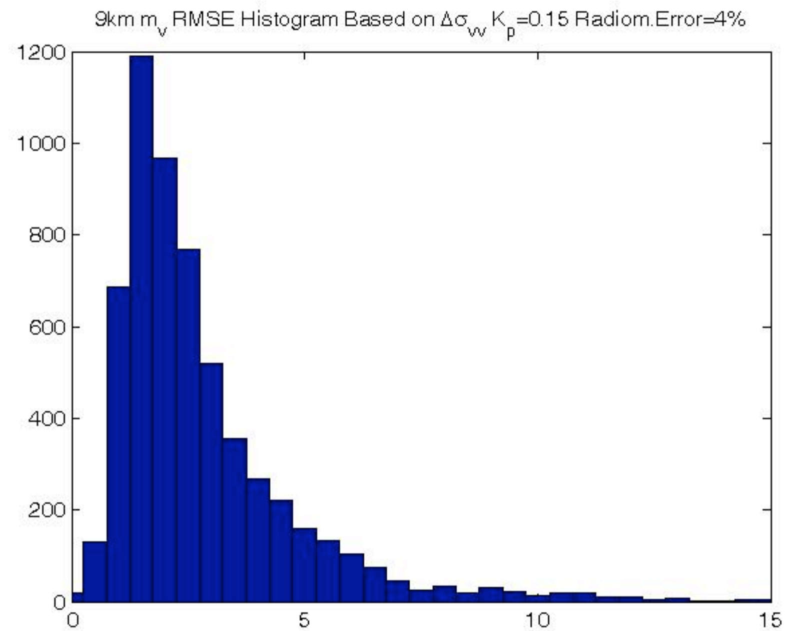
$$K_p = \frac{1}{\sqrt{N}}\left(1 + \frac{2}{SNR} + \frac{1}{SNR^2}\right)^{\frac{1}{2}}$$

$$\sigma_{pp} = \overline{\sigma}_{pp}\left(1 + K_p \cdot \eta\right)$$

where η is *N*(0,1)

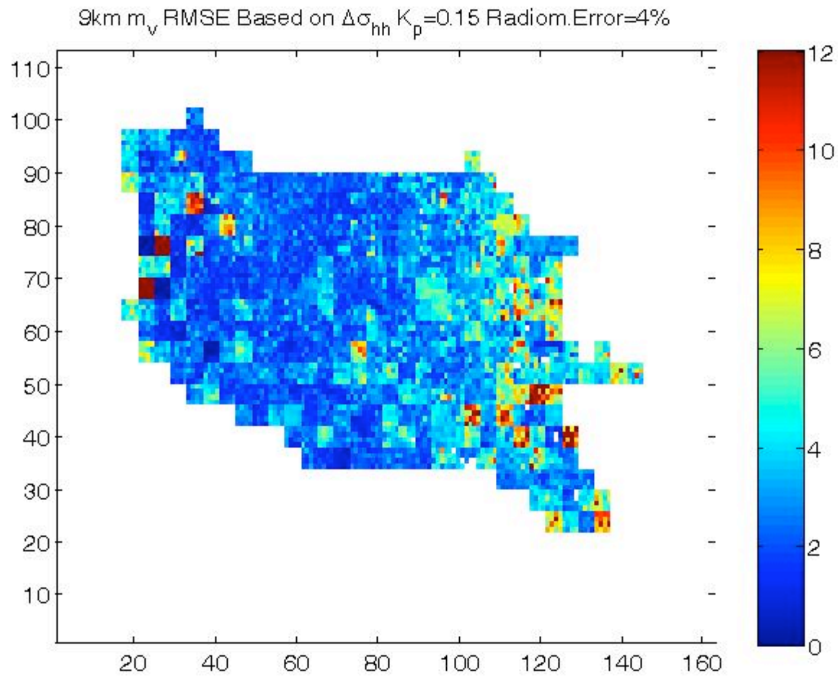


Time-series approach at 10 km



VV-pol Application.

4% Retrieval error of radiometer
K_p=0.15 error for radar



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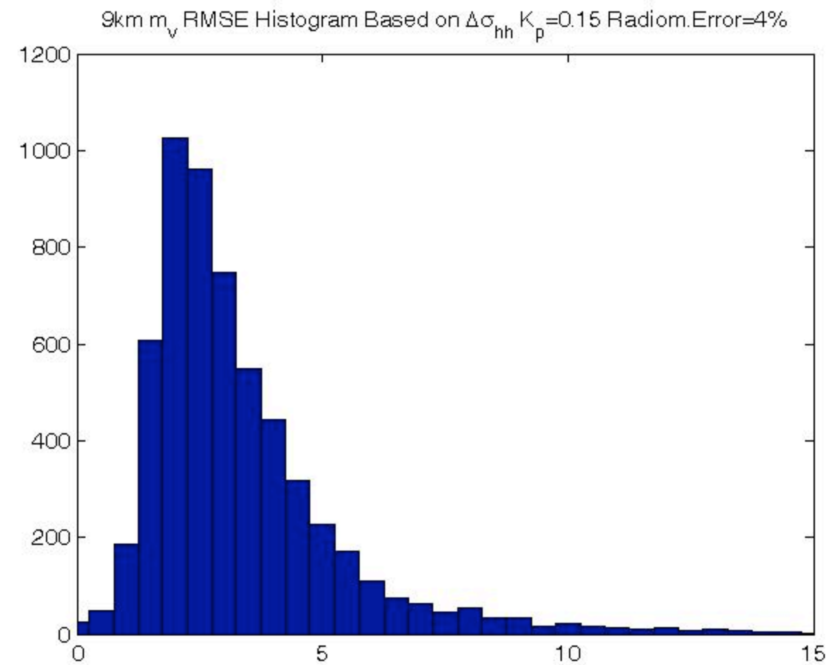
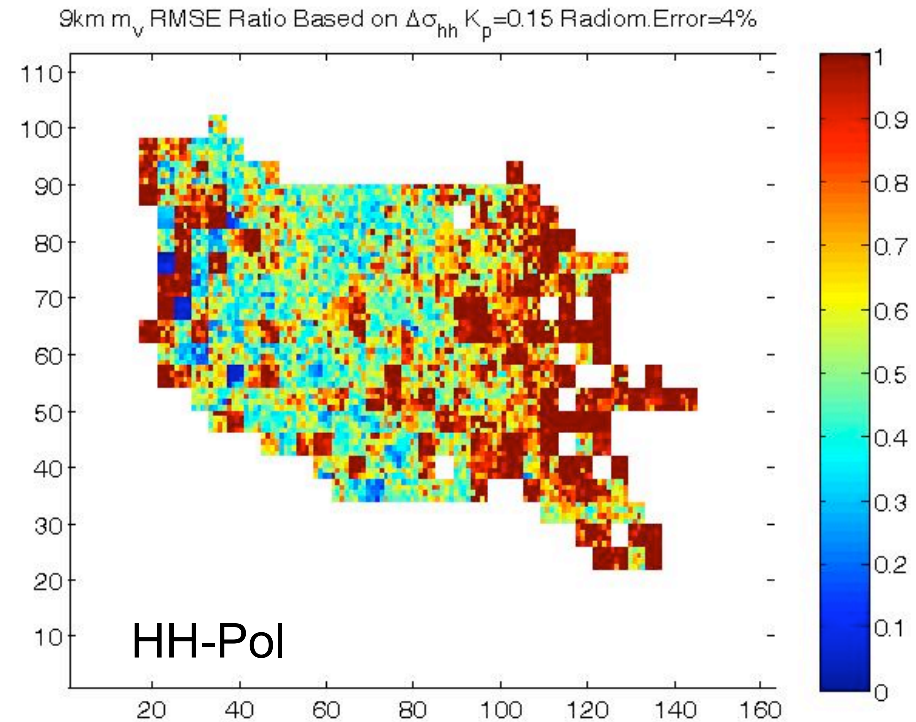


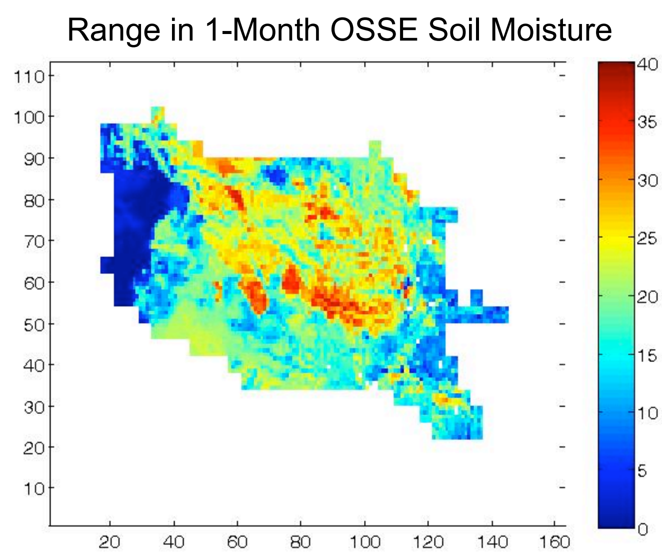
HH-pol Application.

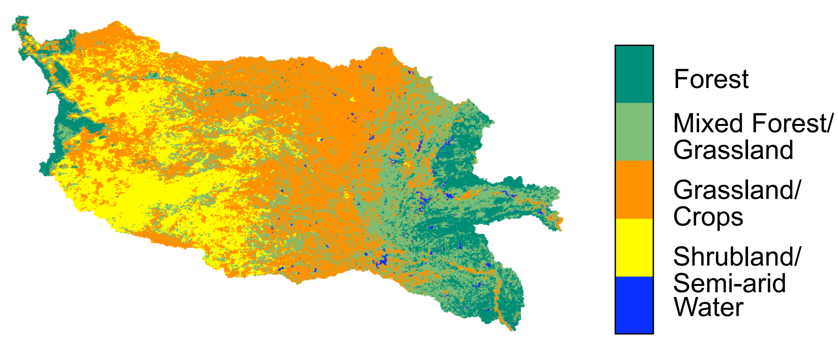
4% Retrieval error of radiometer
K_p=0.15 error for radar

Ratio of Algorithm RMSE to 'Minimum Performance' RMSE

Where <1 value is added with active-passive approach







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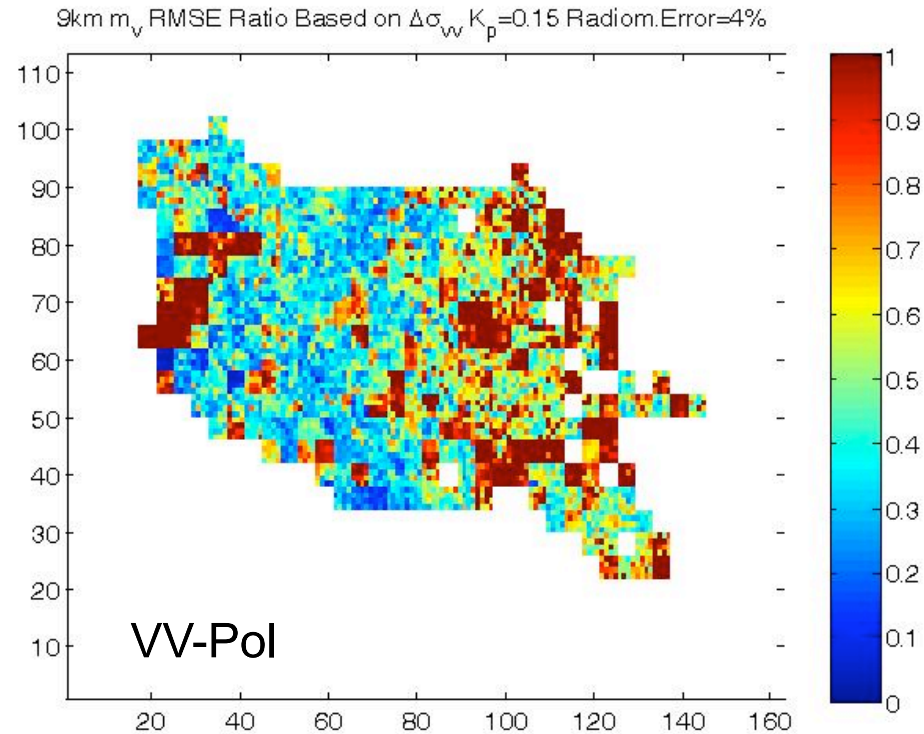
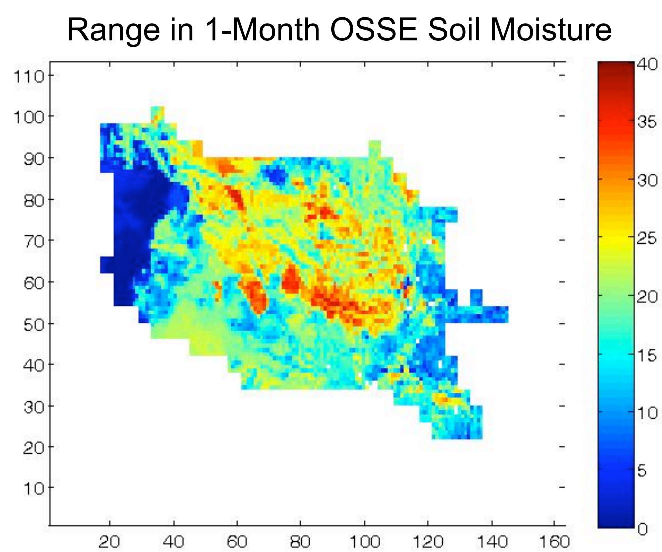
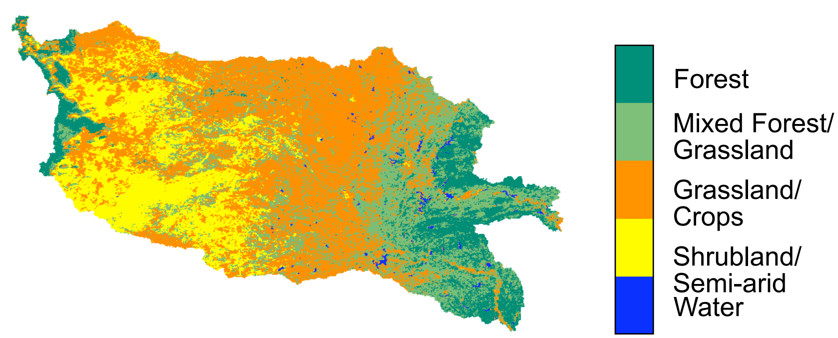
Where <1 value is added with active-passive approach







Conclusions:

1. Coincident active radar and passive radiometer L-band measurements offer varying advantages: Resolution for radar and retrieval accuracy for radiometer

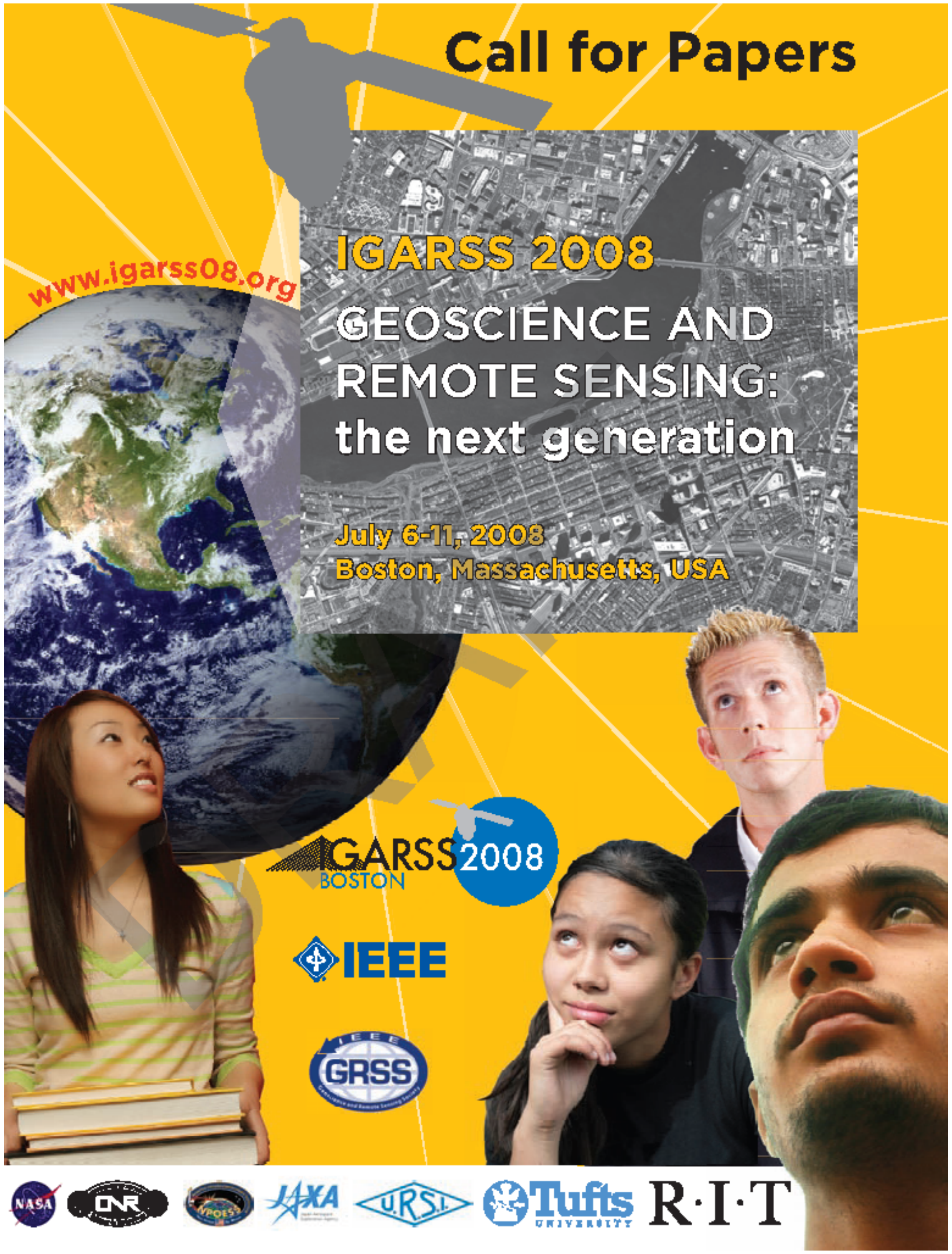
2. Physics-based inverse model for radar is difficult to define

3. At constant incidence angle the change in radar signal isolates the soil moisture signal (slow-varying vegetation and surface roughness contributions)

4. An algorithm can be defined for multi-scale measurements that has three isolated and testable assumptions:
   I. Logarithm of radar backscatter scales linearly with soil moisture
   II. Slope (due primarily to vegetation and roughness) and backscatter fluctuations (due to soil moisture) themselves are uncorrelated
   III. Variations in vegetation type occur principally at scales larger than tens of kilometer.

5. OSSE results show that radar-radiometer synergy is promising for hydrometeorology 10 km soil moisture data product from SMAP mission approach.

6. Tests using PALS and other field experiment data is next.



See you in Boston!